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STRUCTURAL HEALTH MONITORING OF END PLATE STEEL BEAM-COLUMN CONNECTION USING EMI TECHNIQUE: NUMERICAL SIMULATION

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ABSTRACT

Recent advances in structural health monitoring (SHM) techniques, particularly the electro-mechanical impedance (EMI) methodology, had proven to be a successful, time-saving, and simple non-destructive evaluation process (NDE). The assessment of structural performance in terms of serviceability, ultimate limit states, durability, and catastrophic failure has long been a major concern. Early diagnosis of structural faults is critical for condition monitoring of any structure, especially after a natural disaster like an earthquake. The sensing network, data processing and analysis, damage assessment, and decision-making are all critical components of an SHM approach. The structural health monitoring technique used in this study is based on Electro-mechanical Impedance (EMI) which analyses the signature of vibrations of the target member or structural system. For a long time, this has been considered by many researchers globally. A key aspect of the EMI technique is the use of Lead Zirconate Titanate (PZT) patches which function as an actuator as well as a sensor. End plate steel beam-column connection is a very crucial member of the steel structure. In this research, a deficient end plate steel beam-column connection subsequently strengthened with carbon fibre reinforced polymer sheets was simulated using a finite element analysis software ANSYS. The health monitoring of this member was performed using modelled PZT transducer in ANSYS itself. It was concluded that the simulated electro-mechanical impedance technique using finite element software was capable of identifying the defects or deficiency as well as strength gained by means of retrofitting.

Keywords: Structural Health Monitoring, PZT Patch, EMI Technique, ANSYS.

1. INTRODUCTION

Structural Health Monitoring is defined as the process of implementing a strategy for identifying damage and evaluating the health of engineering structures. SHM monitors the structural performance and operational environments of engineering structures using sensing systems and associated hardware and software. SHM entails observing a structure over time, using periodically sampled structural response and operational environment measurements from an array of sensors, and then evaluating the structure’s current state and future performance. For long-term SHM, the output of this process is periodically updated information about the structure’s ability to perform its intended function, considering the inevitable aging and degradation caused by operational environments. Damage is defined here as changes to a structure’s material and geometric properties that affect the structure’s current state and future performance. An SHM strategy’s objectives can be broken down into five levels: Level I: Damage detection, which provides a qualitative indication that damage may exist in the structure. Level II: Damage localization, which provides information about the likely location of the damage. Level III: Damage classification, which provides information on the type of damage. Level IV: Damage assessment, which provides an estimate of the extent of the damage. Level V: Damage prognosis, providing information about the structure’s safety, such as an estimate of remaining useful life. The level in the preceding order represents an increasing understanding of the damage state. A higher level usually necessitates knowledge of all lower levels.[3] With the development of sensors, a piezoelectric material called Lead Zirconate Titanate (PZT) has been widely used as both actuator and sensor and has made the Electromechanical Impedance (EMI) technique possible. This method has the advantage of detecting the damage remotely. Besides the sensors, the LCR (Inductance L, Capacitance C, and Resistance R) meter is the other key component, which measures the electro-mechanical (EM) admittance of the bonded PZT patch. [2]

1.1.HEALTH MONITORING USING EMI TECHNIQUE

In the EMI technique, a PZT patch is typically bonded to the surface or embedded inside the structure (to be monitored) with a high-strength epoxy adhesive and electrically excited using an LCR meter or an impedance analyzer. In sweep mode, the LCR meter measures the electro-mechanical (EM) admittance of the PZT patch (consisting of the real part, conductance, and the imaginary part, susceptance) over a user-specified frequency range at specified intervals. When plotted as functions of frequency, these measurements form a unique signature of the structure, which can only be altered by physical changes to the structure. When the structure's condition is to be assessed in the future, the signatures are collected and compared to the baseline signature. The consistency of the signature indicates the health of the structure. Any change in the signature indicates the occurrence of damage. Essentially, the LCR meter sends a harmonic voltage signal across the PZT patch at a specific frequency. As a result, deformations occur in the patch as well as the surrounding area of the host structure. The response of this area to the imposed mechanical vibrations is transferred back to the PZT patch in the form of electrical response, as conductance and susceptance signatures. The structural characteristics are reflected in the signatures as a result of this interaction. Any damage to the structure alters the structural characteristics, and thus the signatures. [2] The PZT patch and LCR meter are shown in fig 1 and fig 2 respectively.

Fig.1 Lead Zirconate Titanate (PZT) patch.

Fig.2 LCR Meter.

1.2.DAMAGE INDEX (RMSD)

The quantification of variation in the vibrational signature of the structure is obtained using various statistical techniques such as Root Mean Square Deviation (RMSD), Mean Absolute Percentage Deviation (MAPD), Relative Deviation (RD), and Correlation Coefficient Deviation (CCD) Ursu et.al. (2016). Among these the most commonly used statistical technique is by calculating the normalized root mean square deviation (RMSD) which can be used as a damage index. The RMSD can be measured using following formula

$$RMSD = \sqrt{\frac{\sum_{k=1}^{N}(G_k^1 - G_k^0)^2}{\sum_{k=1}^{N}(G_k^0)^2}} \qquad (1)$$

where,

G_k^1= conductance at ith point after damage

G_k^0= conductance before damage

Σ = standard deviation

2. LITERATURE REVIEW

Bhalla and Soh (2004) presented a procedure to conduct the health monitoring of structural systems from the admittance signatures of a surface-mounted PZT patch. Yan et.al., (2011) compared the results of post-embedded a PZT sensor smart aggregate in an existing RCC bridge pier. It was tested by applying reverse cyclic loading and a pre-embed to an RCC pier model and tested using a Shake table. It was observed that the damage indices have a similar trend as the drift ratio and these results were verified by in-situ bridge pier results.

Dan sheng wang et al. (2013) presented an approach based on electromechanical admittances (inverse of impedance) of several PZT patches and used damage index as correlation coefficient (CC). Three PZT patches were attached to the surface of a plain concrete beam at predetermined intervals and the occurrences of various cracks in a beam were monitored by detecting the electromechanical admittance signature of each PZT at different frequency bands and the damage sites and severity were also assessed. Naveet Kaur and Suresh Bhalla (2014) demonstrated an experiment achieving energy harvesting as well as health monitoring using a concrete vibration sensor (CVS) on the reinforced concrete beam. The performance of the embedded concrete vibration sensor was compared with surface bonded PZT. The results proved that the PZT can be used as an energy harvester when not in use and also showed that embedded CVS is more sensitive and effective in detecting the damages than surface bonded.

Suraj N. Khante and Shruti R. Gedam (2016) performed a test on reinforced concrete beams with the help of embedded PZT as a smart aggregate. The result showed that conductance signature is more effective than susceptance signature and also very effective results were obtained using embedded PZT. Moin ul Haq, S. Bhalla, Tabasum Naqvi (2016) tested two vertical RC columns of different characteristics which are embedded with concrete vibration sensor (CVS) under fatigue loading conditions using a shake table. It was observed that natural frequency which is a direct measure for stiffness decreased with an increase in damage and the remaining life of the RC column under fatigue loading was estimated by deriving the formula.

Rankhamb and Khante (2016) presented a procedure to detect the damage of curved surfaces and also studied the effect of high temperature variation along with detecting progressive weakening of pipe specimen using advanced PZT patch. They concluded that advanced PZT is location-sensitive even for structures subjected to high heat and progressive weakening was effectively identified. Demi Ai, C Lin, and H Zhu (2020) used the EMI technique to monitor the age of strength gain of concrete in which admixture i.e., accelerator or retarder is added. Two types of PZT transducer as aluminum and cement embedded PZT was proposed. The result showed the concrete hydration increased by accelerator or retarder was successfully monitored using EMI signature. The indicators indicated that the aluminum embedded PZT had better performance than cement embedded PZT.

The results from these studies had established that the structural health monitoring with the use of EMI Technique is very effective and easy to carry out and record data. However, none of the studies have been performed on simulation of the EMI technique and end plate steel beam-column connection monitoring. In this paper, end plate steel beam-column connection was modelled using ANSYS and health monitored with the help of modelled PZT. A similar model was created and monitored but this time a damage was induced. This damaged model was retrofitted using CFRP laminate and health monitoring of retrofitted model was performed. The strength gain was checked using the damage index of EMI technique.

3. SYSTEM DEVELOPMENT

A end plate steel beam-column connection was modelled using finite element analysis software i.e. ANSYS. The dimensions of the end plate steel beam-column connection are shown in the following figure 3.

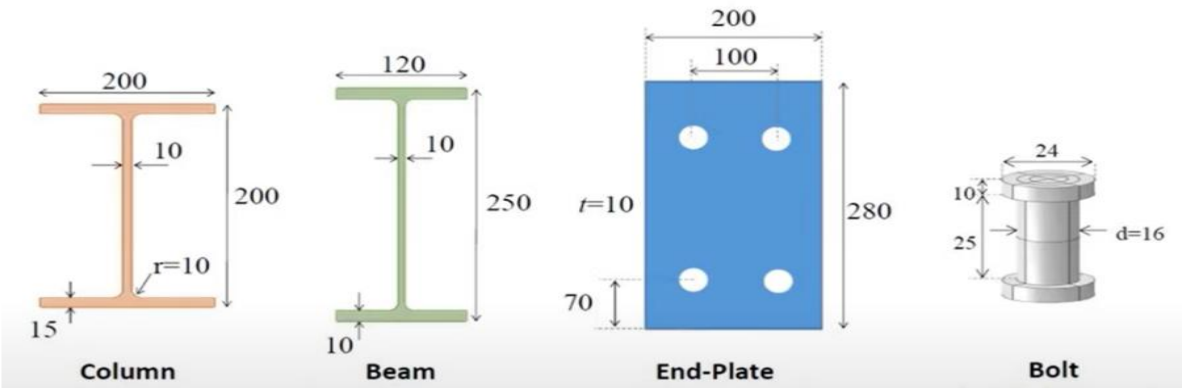

Fig.3 Dimensions of end plate steel beam-column connection

In this member a pre-defined properties of structural steel was assigned. The properties of structural steel are given in table 1. The model came to shape in the SpaceClaim of workbench ANSYS which is called the geometry of the project. The column was fixed at the bottom end and the load was applied at the end of the beam of intensity 2500N & at top of column of 20 kN respectively.

Table 1. Properties of structural steel.

Property	**Steel**
Density (kg/m^3)	7850
Youngs Modulus (Pa)	2 x 10^{11}
Poison's ratio	0.3
Bulk Modulus (Pa)	1.6667 x 10^{11}
Shear Modulus (Pa)	7.6923 x 10^{10}
Tensile Yield Strength (Pa)	2.5 x 10^8
Compressive Yield Strength (Pa)	2.5 x 10^8
Tensile Ultimate Strength (Pa)	4.6 x 10^8

The PZT Patch modelled was of dimension 10 x 10 x 0.3 mm at a distance of 300 mm from the end of the beam. The tetrahedron meshing was done in the model section of the workbench ANSYS. The preliminary analysis was done and total deformation was noted.

After preliminary analysis, the whole model was imported in APDL ANSYS for further harmonic analysis of the member. In APDL the properties of the PZT Patch was assigned which was selected as steel component in the workbench using modify attribute option. Properties of Lead Zirconate Titanate (PZT) is shown in table 2. These values were fed manually in the APDL by assigning the patch as SOLID 5 element whereas the steel properties were directly imported from the workbench. Density, anisotropic elasticity, and piezoelectric strain coefficients were applied to the PZT as mentioned in the table but, the permittivity values were converted into relative permittivity to feed into the ANSYS APDL so the values of electric permittivity

Table 2. Properties of Lead Zirconate Titanate (PZT) Patch

Properties	**Symbols**	**Values**	**Unit**
Density	ρ	7800	kg/ m^3
Anisotropic elasticity (compliance)	S_{11}	15	$10^{-12}m^2$/ N
	$S_{22}=S_{33}$	19	
	$S_{12}=S_{21}$	-4.5	
	$S_{13}=S_{31}$	-5.7	
	$S_{23}=S_{32}$	-5.7	
	$S_{44}=S_{55}$	39.0	
	S_{66}	49.4	
Electric Pennittivity	e_{11}^T	1.75	10^{-8} F/ m
	e_{22}^T	1.75	
	e_{33}^T	2.12	
Piezoelectric Strain Coefficents	d_{31}	-2.1	10^{-10}m/ V
	d_{32}	-2.1	
	d_{33}	5.0	
	d_{24}	5.8	
	d_{15}	5.8	

were divided by 8.8541878128 x 10^{-12} Fm^{-1} i.e., permittivity constant to get relative permittivity. After applying all the properties of PZT Patch the loads were applied on the Patch i.e., the potential difference was applied to it. So a constant load of 1 volt was applied on all the nodes of the outer face of the PZT patch and 0 volt was applied on the inner face which was attached to the steel.

Then the model were analyzed by using the harmonic analysis type for 20 substeps of the frequency range of 0-400kHz. Damping was applied to the structure with the stiffness matrix multiplier of $3e^{-9}$. The results were obtained in the Time-History post processing. Similarly, there were total of three models were created and the signature of these created models were obtained. The conductance and susceptance signature of the first model was considered as baseline signature because first model was representing the healthy model. The second model was created as the cracked model in which the crack was induced on the beam near the connection as a delamination crack. Afterwards, this cracked model was monitored using the EMI Technique. In the third model, the cracked model was retrofitted using CFRP laminate of 2mm thickness using epoxy and then the retrofitted model was monitored using the same process as other two were monitored. In all the three models the properties of steel, dimensions of model, position of PZT patch, load applied for preliminary analysis was kept constant so that comparison can be made between these three models.

4. RESULTS AND DISCUSSION

4.1.Preliminary analysis:

As mentioned above the finite element analysis and simulation in ANSYS Workbench was done by applying 2500N load on all the three models in order to get the maximum deformation which was further used to calculate the stiffness. The stiffness and deformation of all three models are shown in table 3. The total deformation of all the models are shown in fig 4.a, 4.b, and 4.c.

Table 3. Deformation and Stiffness of models.

Sr. no	Model name	Deformation(mm)	Stiffness(N/mm)
1	Healthy model	0.11695	21376.65
2	Cracked model	0.12474	20041.68
3	Retrofitted model	0.10984	22760.37

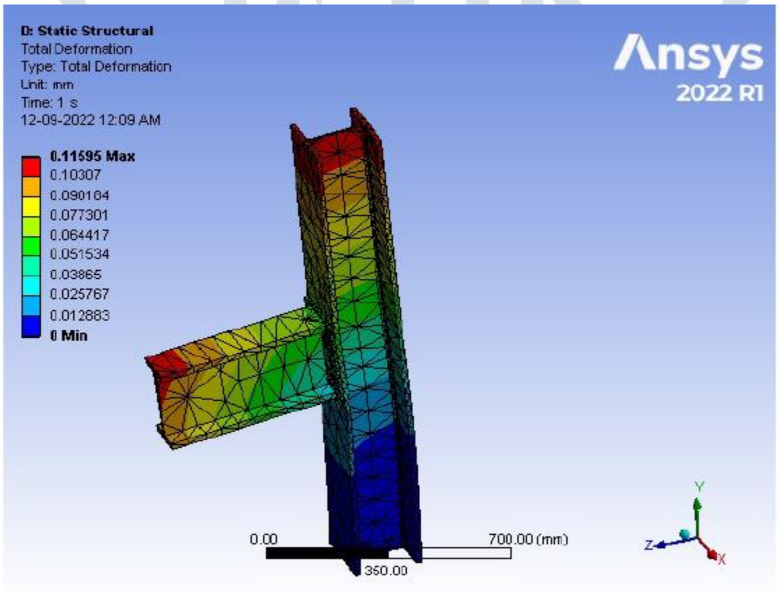

Fig. 4.a. Healthy model.

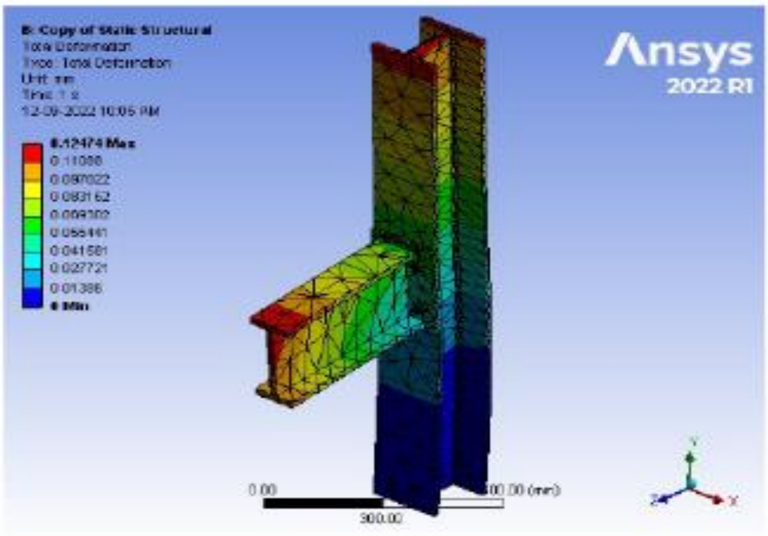

Fig. 4.b. Cracked model.

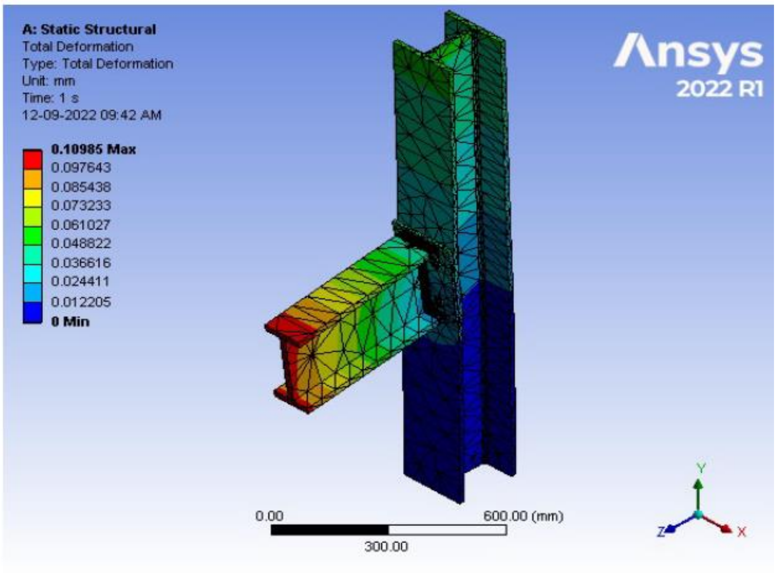

Fig. 4.c. Retrofitted model.

4.2.Electro-mechanical admittance:

The electro-mechanical admittance of the PZT patch were obtained during ANSYS APDL finite element modelling and simulation. All the three models were simulated and monitored using the EMI technique of SHM in which the admittance value of 20 sub-steps were obtained at a frequency range of 0-400kHz. The admittance had a complex value which consist of a real part and imaginary part. The real part represents the conductance and imaginary part represents the susceptance. The values of conductance were plotted against frequency to get the conductance signatures of these models. Similarly, susceptance were plotted against frequency to get susceptance signature of these models.

The conductance and susceptance signature of the healthy model (baseline signature) are shown in fig 5.a and 5.b respectively. Similarly the conductance and susceptance signature of cracked and retrofitted models are shown in fig 6.a ,6.b and 7.a , 7.b respectively.

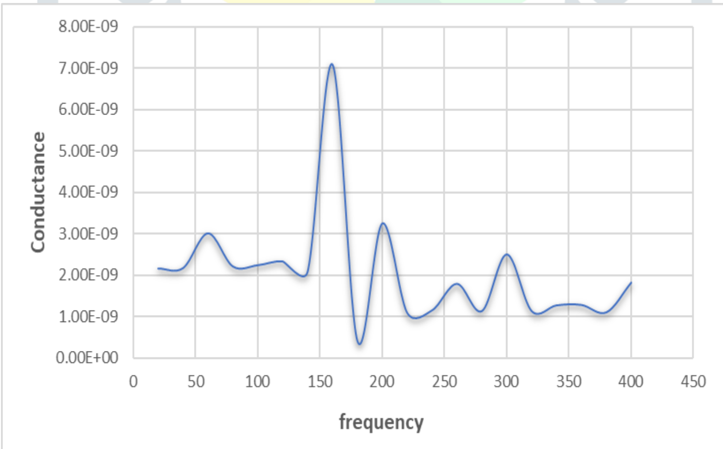

Fig. 5.a. Conductance vs frequency signature of healthy model.

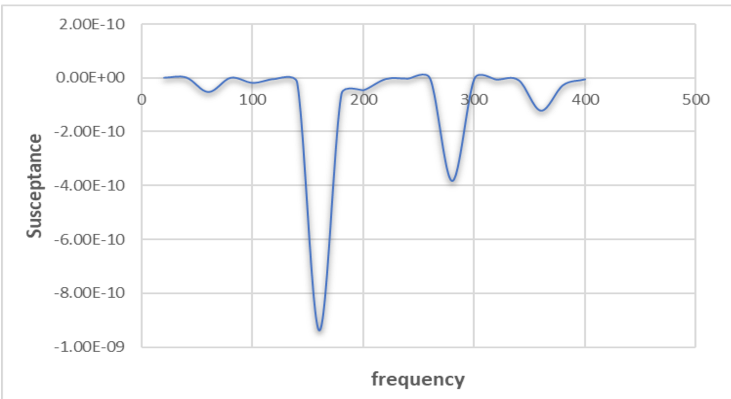

Fig. 5.b. Susceptance vs frequency signature of healthy model.

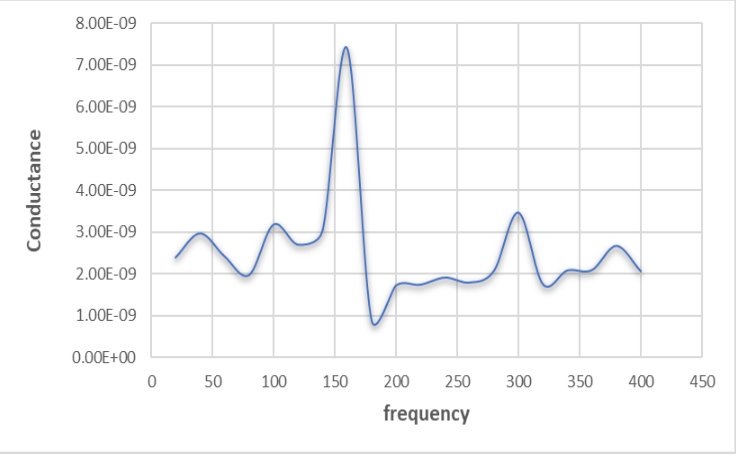

Fig. 6.a. Conductance vs frequency signature of Cracked model

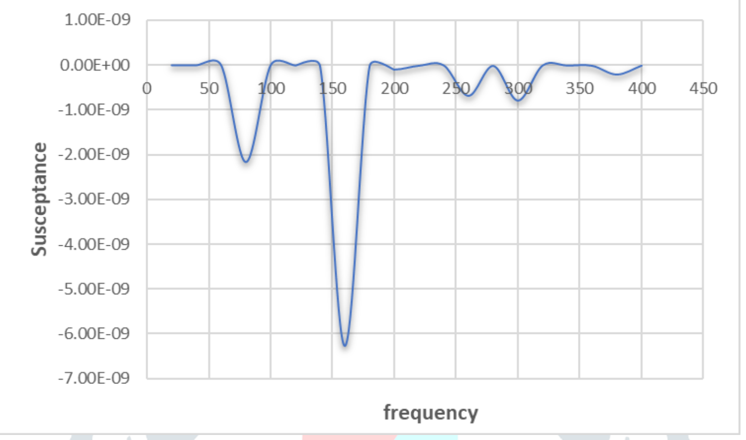

Fig. 6.b. Susceptance vs frequency signature of Cracked model.

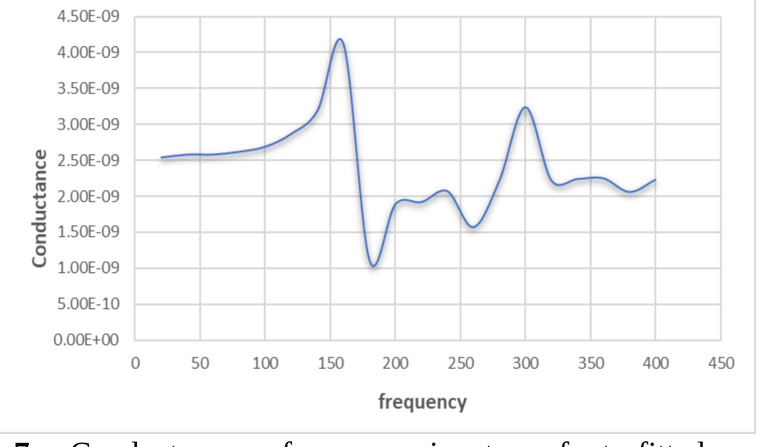

Fig. 7.a. Conductance vs frequency signature of retrofitted model.

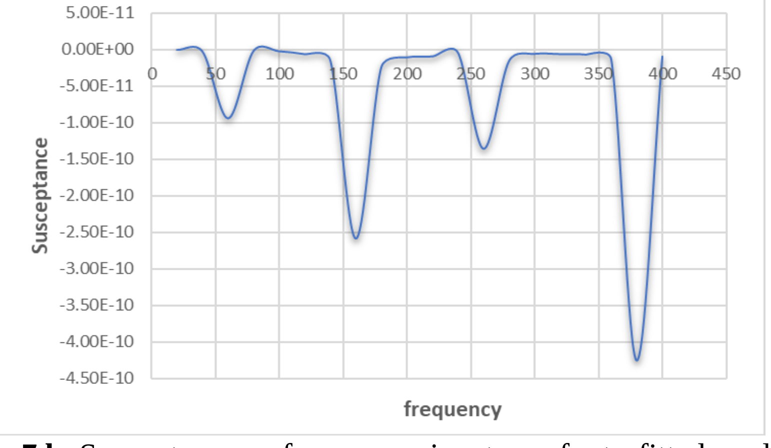

Fig. 7.b. Susceptance vs frequency signature of retrofitted model.

Fig 8.a. Shows the conductance signature of all three models together and similarly, Fig 8.b. Shows the susceptance signatures of all three models. In both graphs the blue line shows the baseline signature, the orange line shows the signature for the cracked model, and the green line shows the retrofitted column signature. These signatures of the structure were disclosing the characteristics of the structure such as inherent stiffness, damping, and mass distribution. As the cracked model was retrofitted using CFRP the stiffness of the structure increases and the conductance values of the retrofitted model decreased as seen in the conductance signature. The conductance of the model increases due to induced crack in the healthy model which concludes that conductance generally increases as the stiffness of the model decreases and vice versa. From these results a general conclusion can be made that the conductance signature is directly related to the stiffness of the models.

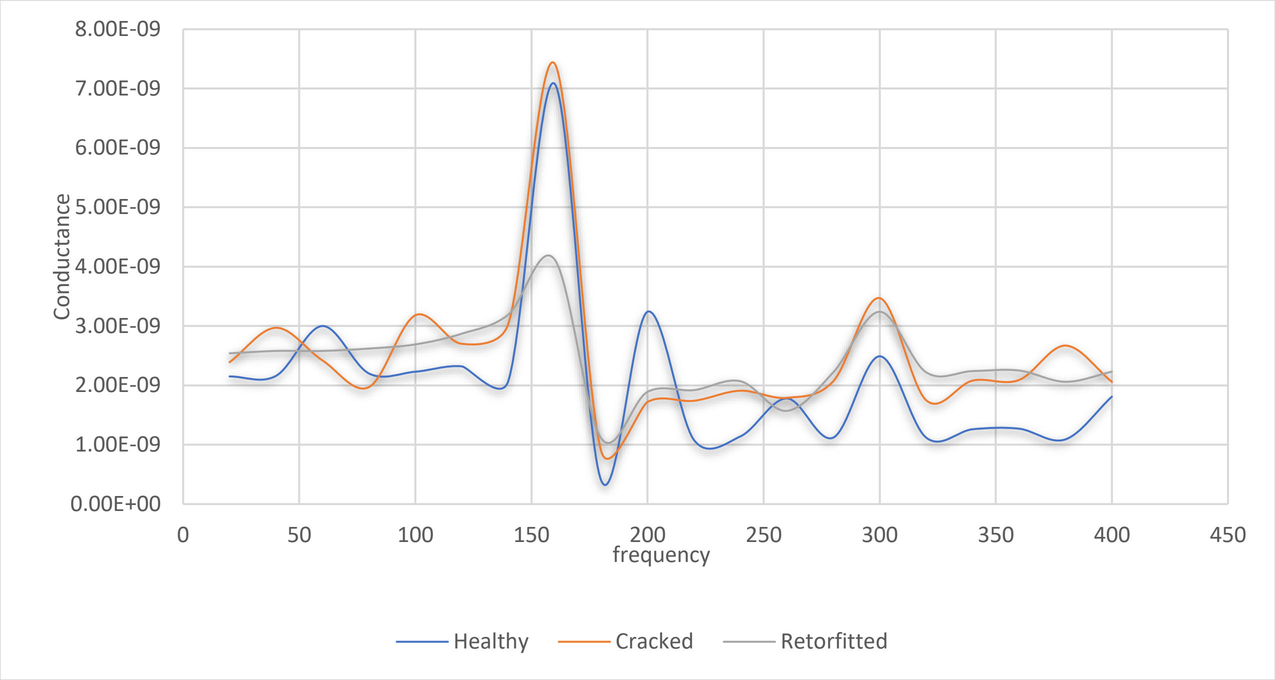

Fig. 8.a. Conductance vs frequency signature of all models.

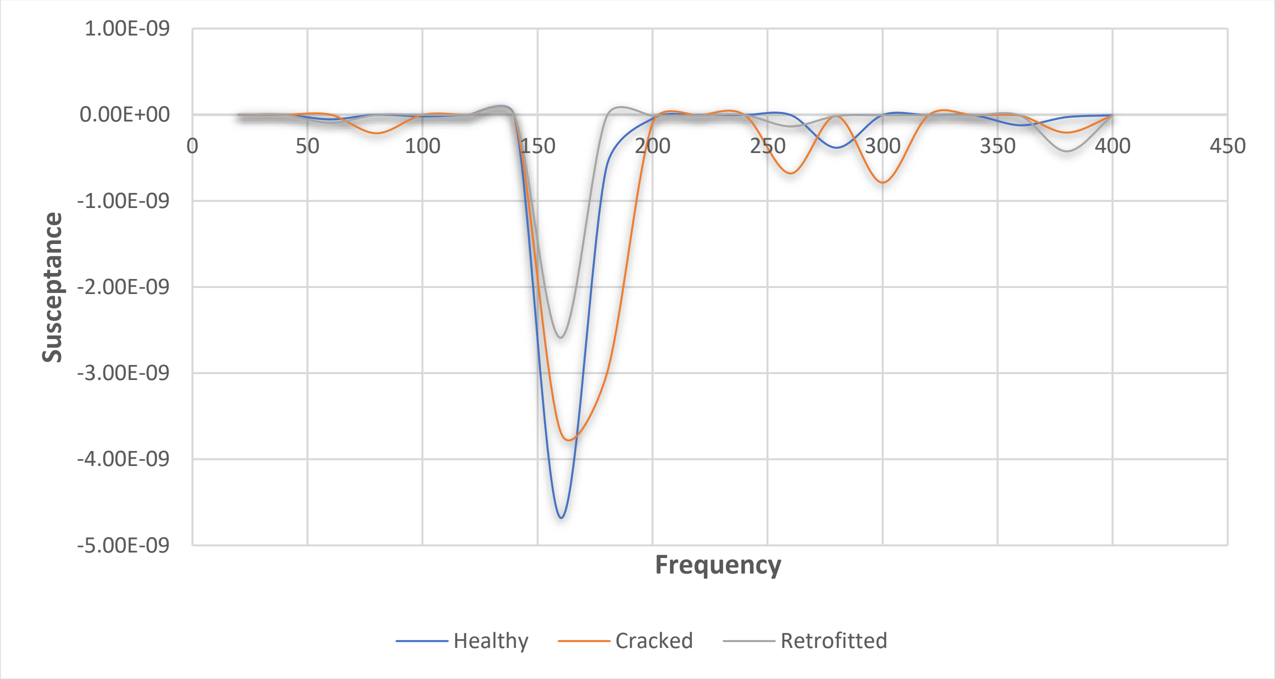

Fig. 8.b. Susceptance vs frequency signature of all models.

4.3.Root-Mean-Square-Deviation:

The RMSDs were calculated keeping the value of conductance of healthy model as a baseline value G_k^0 in equation 1 and the values of G_k^0 were taken as the conductance of cracked and retrofitted model simultaneously to get the RMSD-cracked and RMSD-retrofitted values. The RMSD were calculated for different frequency range because the deviations were large at some ranges as compared to others. RMSD at different frequency range can be seen in fig.9. After calculation of overall RMSD between the range of 0-400kHz it came out to be 0.291for the cracked model and 0.452. These values state that the deviation of the signature of cracked model from the base model is about 29.1%. and that of retrofitted model was 45.2% from the baseline model.

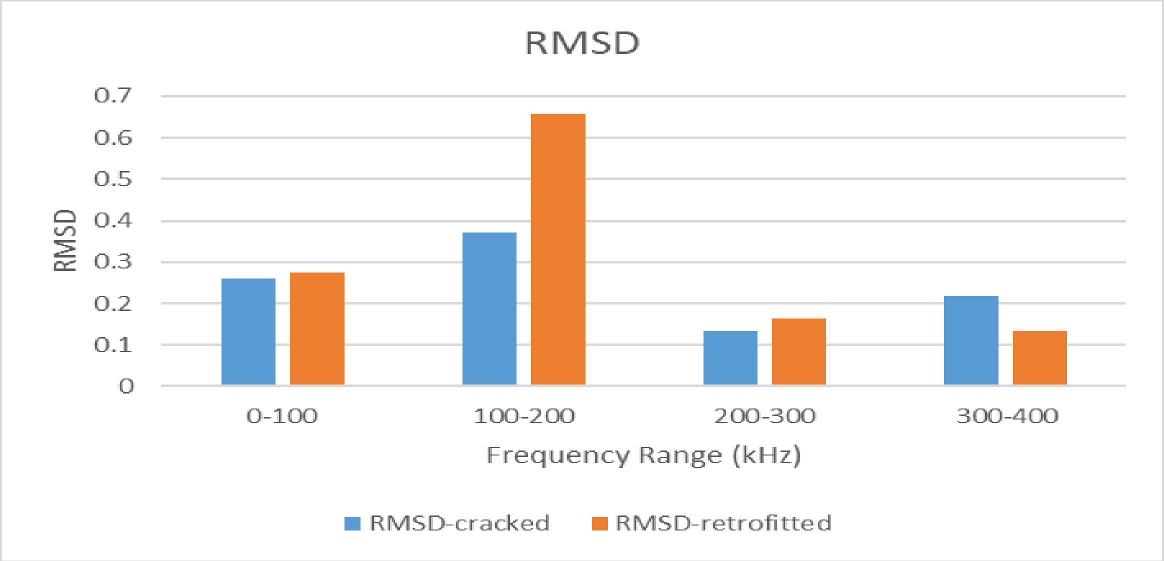

Fig.9. Root Mean Square Deviation.

5. CONCLUSION

In this paper, the PZT sensor was modeled for the health monitoring of end plate steel beam-column connection models using the simulated EMI Technique. From the above work following conclusions were drawn:

- The PZT sensor employed for damage sensing in healthy, cracked, and retrofitted models was found to be very sensitive.
- The conductance signature of the cracked and retrofitted model deviates away from the conductance signature of the baseline model which indicates the change in the stiffness of the member.
- The impending damage was very effectively identified by swapping the frequency in the range of 100 to 200kHz.
- RMSD values of the retrofitted model are found more than that of the cracked model which shows that the member had gained strength after retrofitting which is even more than the healthy member.

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